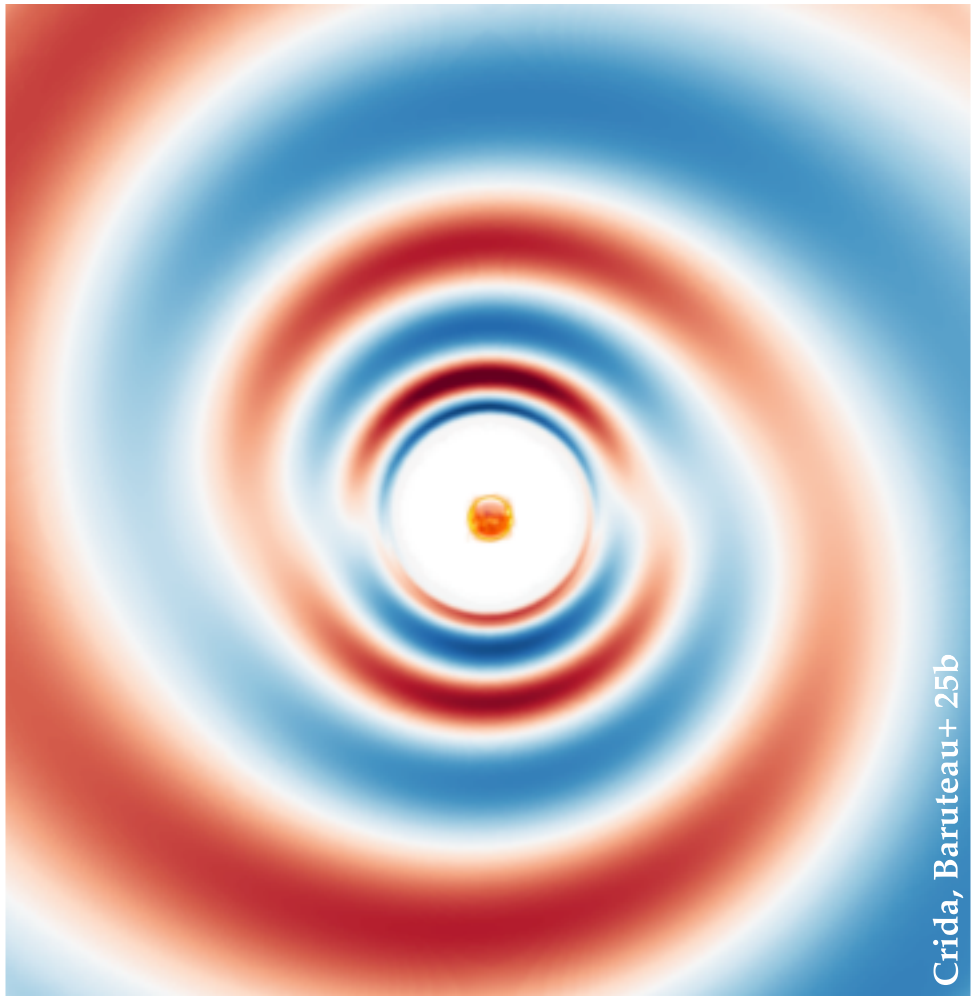
The reflex instability in protoplanetary discs

Clément Baruteau (IRAP)

&

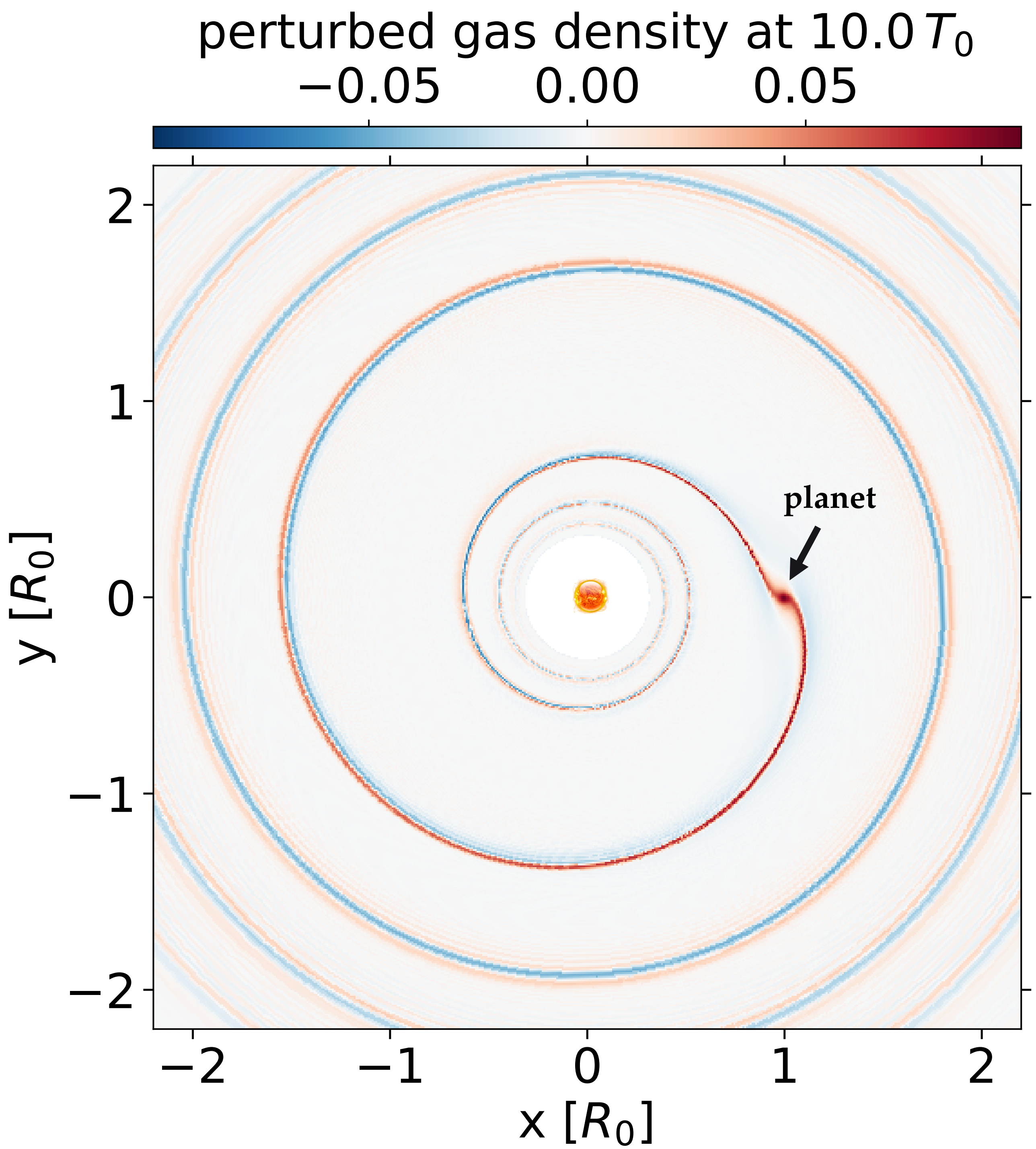
Nathan Magnan (LAGRANGE), **Aurélien Crida** (LAGRANGE),
Jean-François Gonzalez (CRAL), **Philippine Griveaud** (MPIA),
Elena Lega (LAGRANGE), **Frédéric Masset** (UNAM), **Héloïse Méheut** (LAGRANGE)



SF2A / ATEXOS workshop - 25 June 2026

The reflex instability in protoplanetary discs

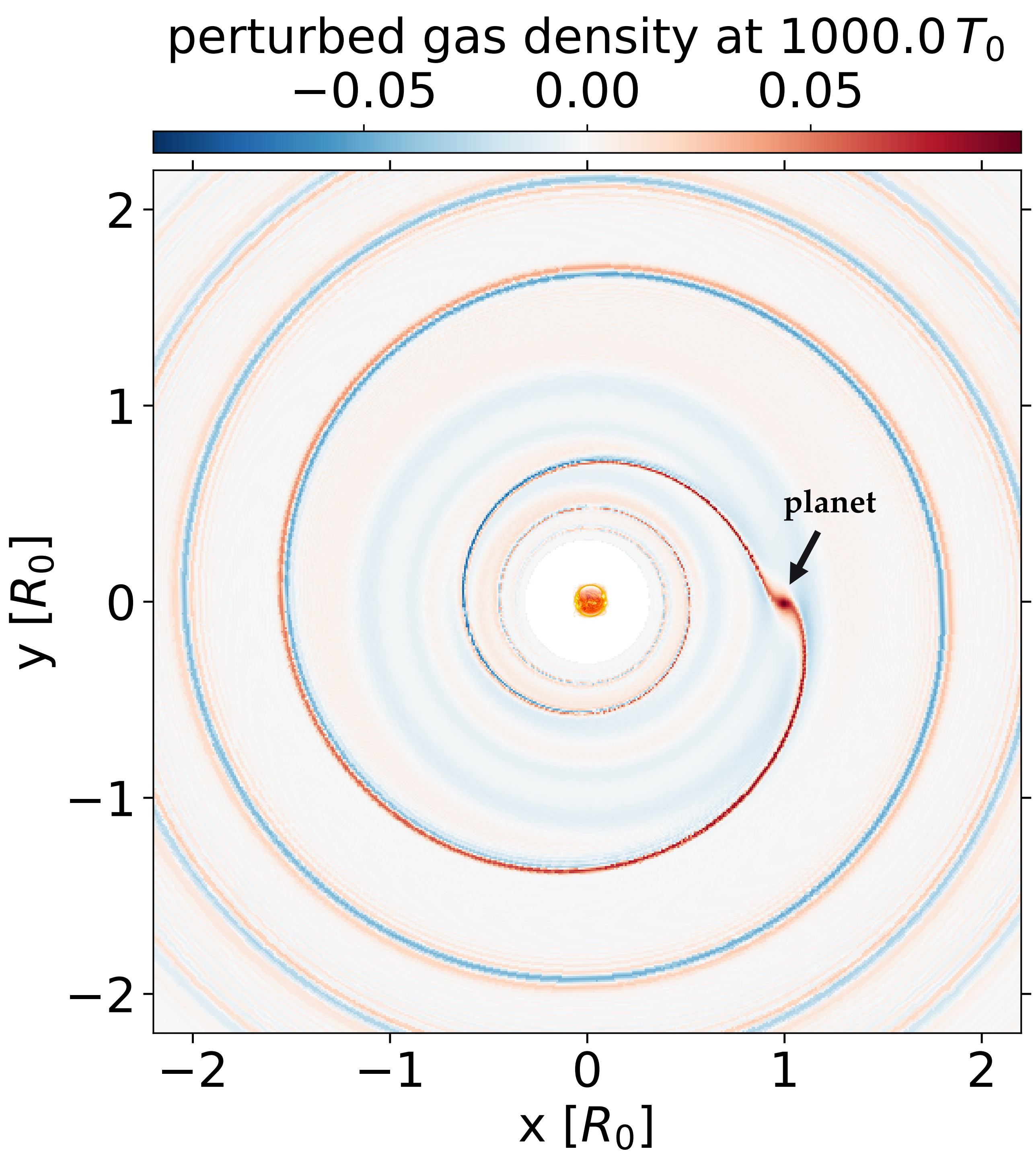
- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
  - example simulation with a 3 Earth-mass **planet** on a **fixed** orbit in a disc with M_{disc} / $M_\star$ ~ 6%



simulation run in the barycentric frame (FARGO-2D1D code)

The reflex instability in protoplanetary discs

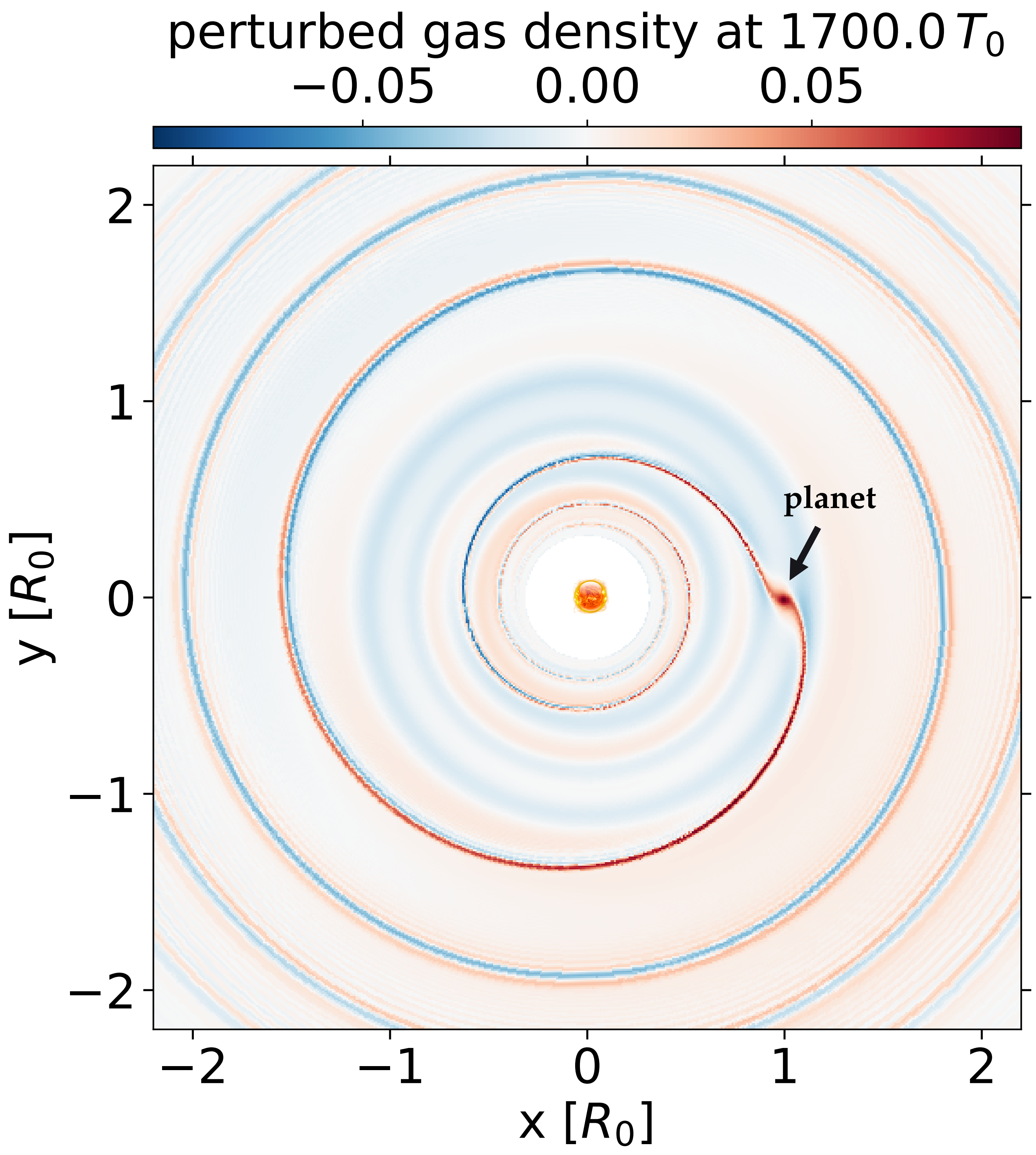
- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
  - example simulation with a 3 Earth-mass **planet** on a **fixed** orbit in a disc with M_{disc} / $M_\star$ ~ 6%



simulation run in the barycentric frame (FARGO-2D1D code)

The reflex instability in protoplanetary discs

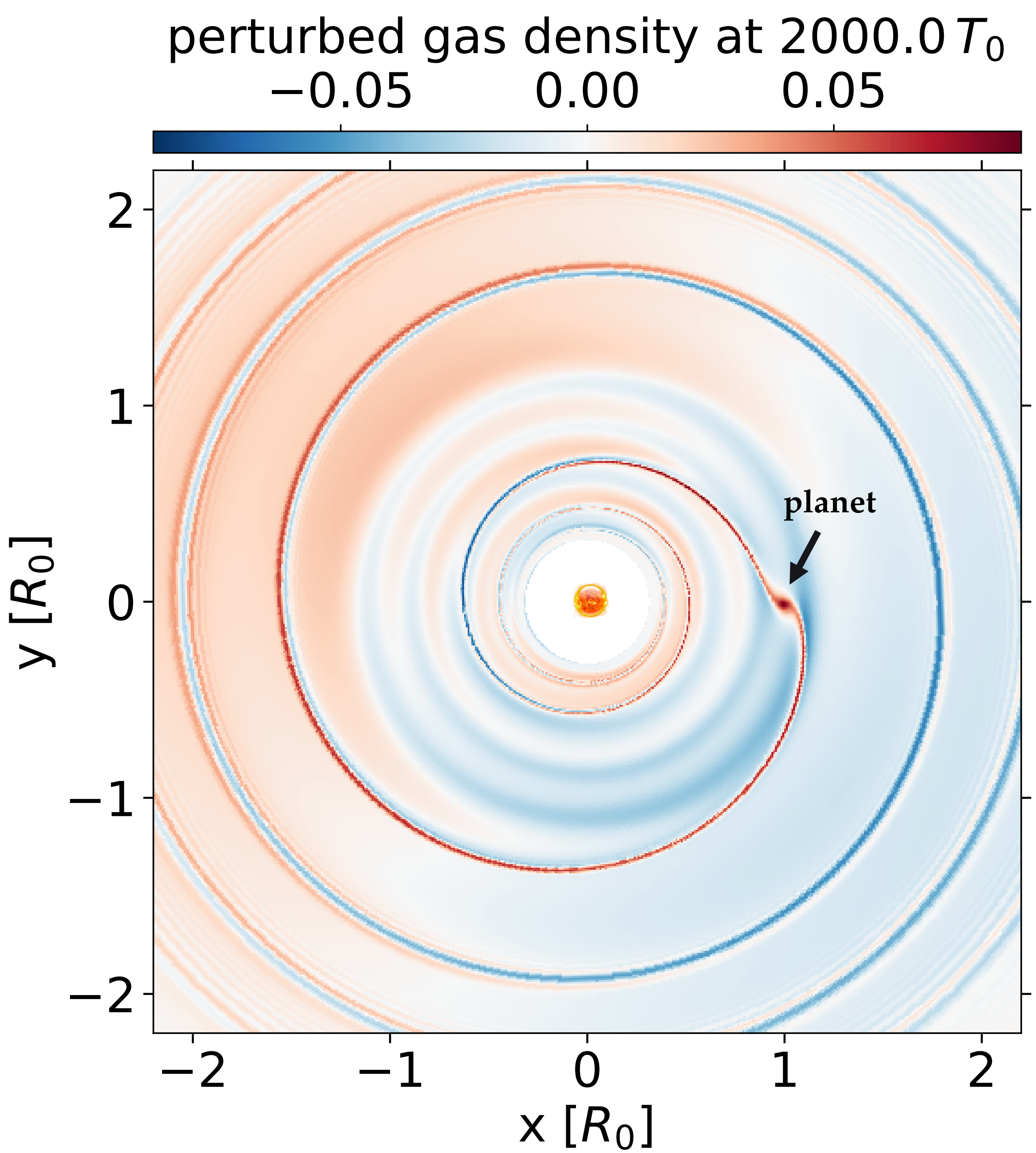
- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
  - example simulation with a 3 Earth-mass **planet** on a **fixed** orbit in a disc with M_{disc} / $M_\star$ ~ 6%



simulation run in the barycentric frame (FARGO-2D1D code)

The reflex instability in protoplanetary discs

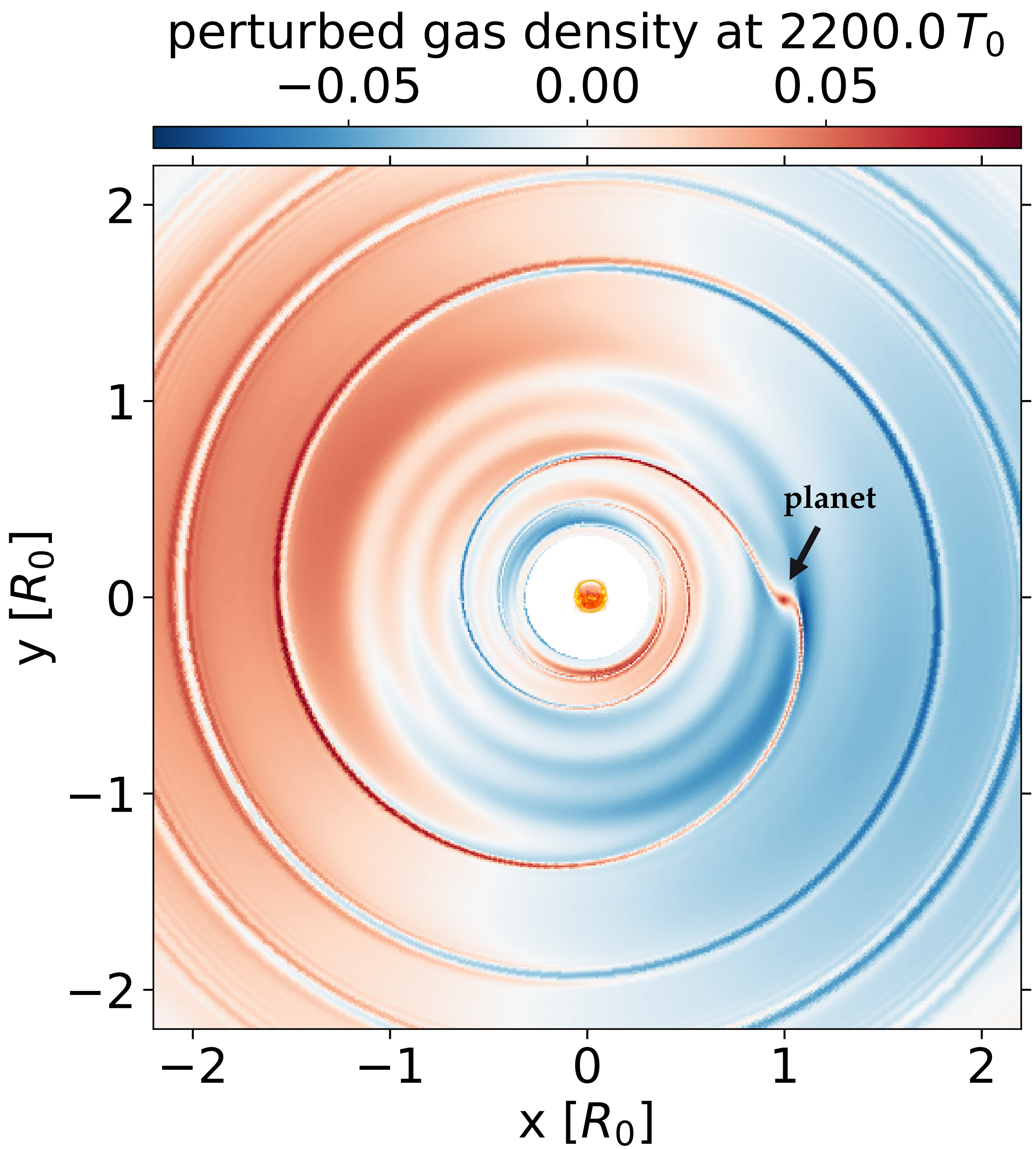
- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
  - example simulation with a 3 Earth-mass **planet** on a **fixed** orbit in a disc with M_{disc} / $M_{\star}$ ~ 6%



simulation run in the barycentric frame (FARGO-2D1D code)

The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
  - example simulation with a 3 Earth-mass **planet** on a **fixed** orbit in a disc with M_{disc} / $M_\star$ ~ 6%



simulation run in the barycentric frame (FARGO-2D1D code)

The reflex instability in protoplanetary discs

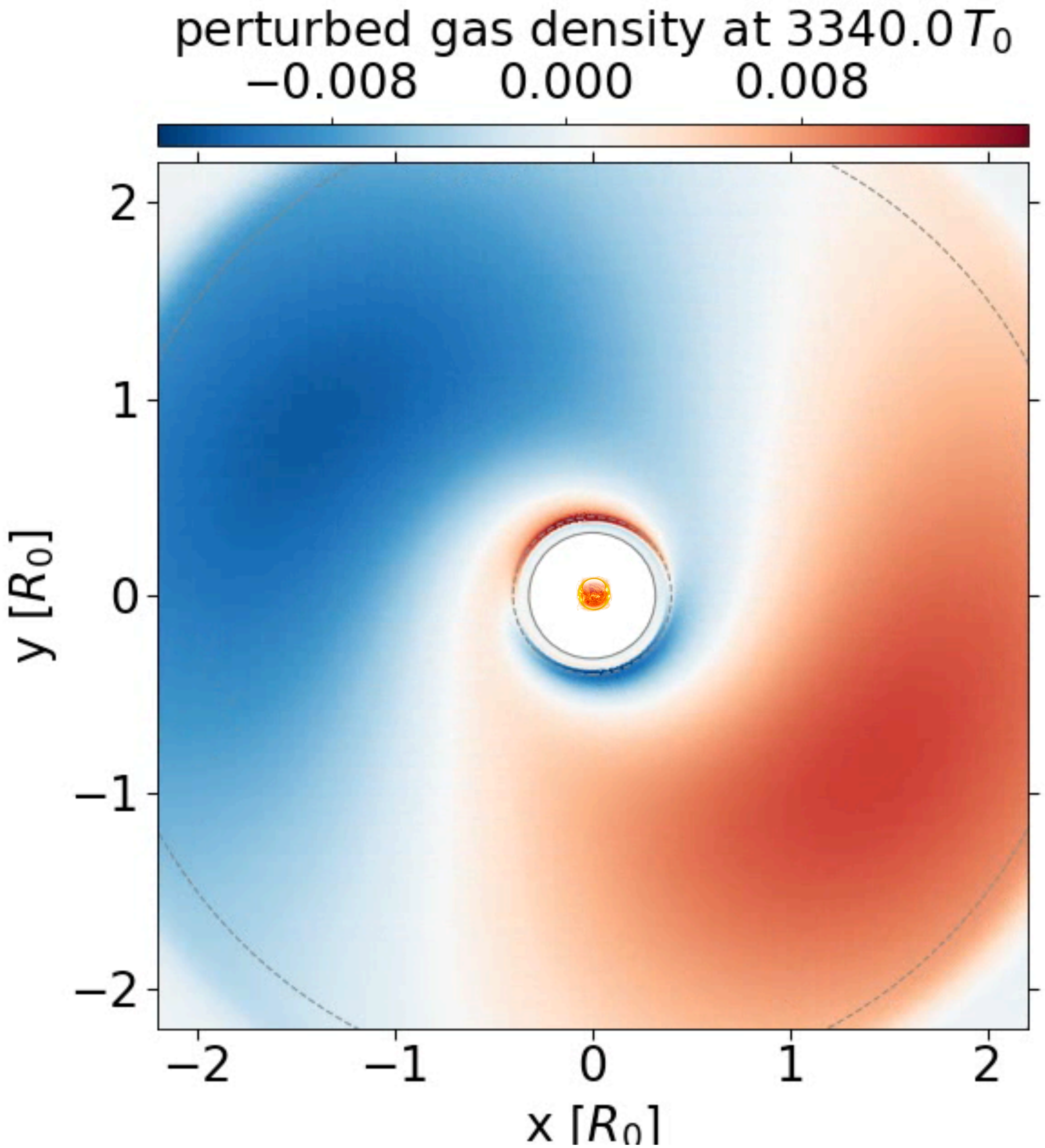
Crida, Baruteau, Gonzalez+ 2025b

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a **planet-free**, but still deliberately **simple** disc model
  - inviscid, isothermal disc with $M_{disc} / M_{\star} \sim 6\%$ (Toomre-Q ~ 4 uniformly)
  - **white noise** at the 0.1% level added to initial disc density to break initial axisymmetry

The reflex instability in protoplanetary discs

Crida, Baruteau, Gonzalez+ 2025b

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is **linear, non-axisymmetric, global**



grid's inner edge

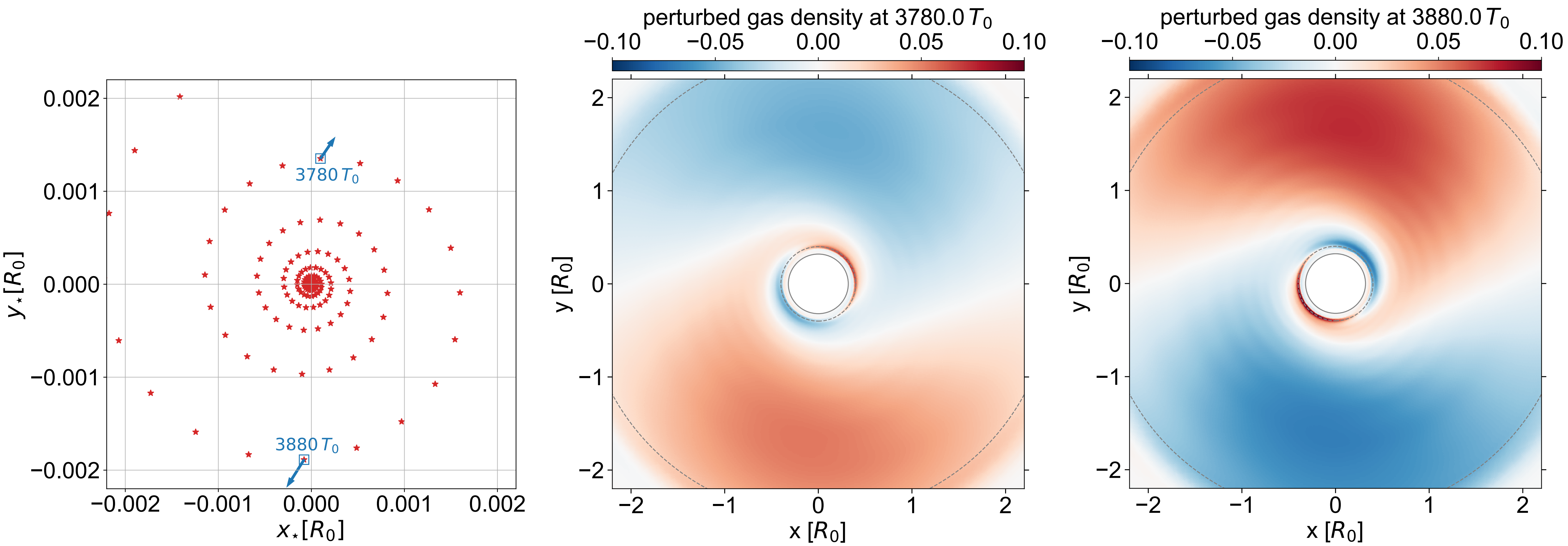
borders of damping layers

simulation run in the barycentric frame (FARGO-2D1D code)

The reflex instability in protoplanetary discs

Crida, Baruteau, Gonzalez+ 2025b

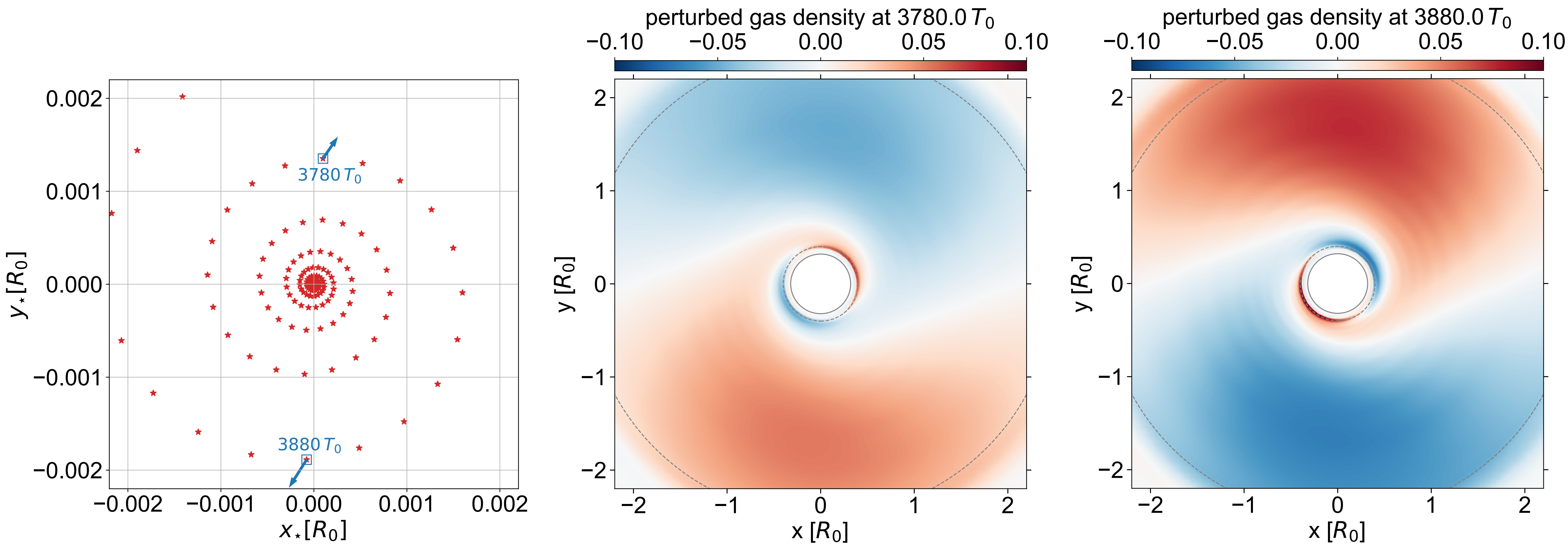
- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a **feedback loop** between an **m=1 mode** in the disc and the **reflex motion** of the **star** around the centre-of-mass → "the reflex instability"



The reflex instability in protoplanetary discs

Crida, Baruteau, Gonzalez+ 2025b

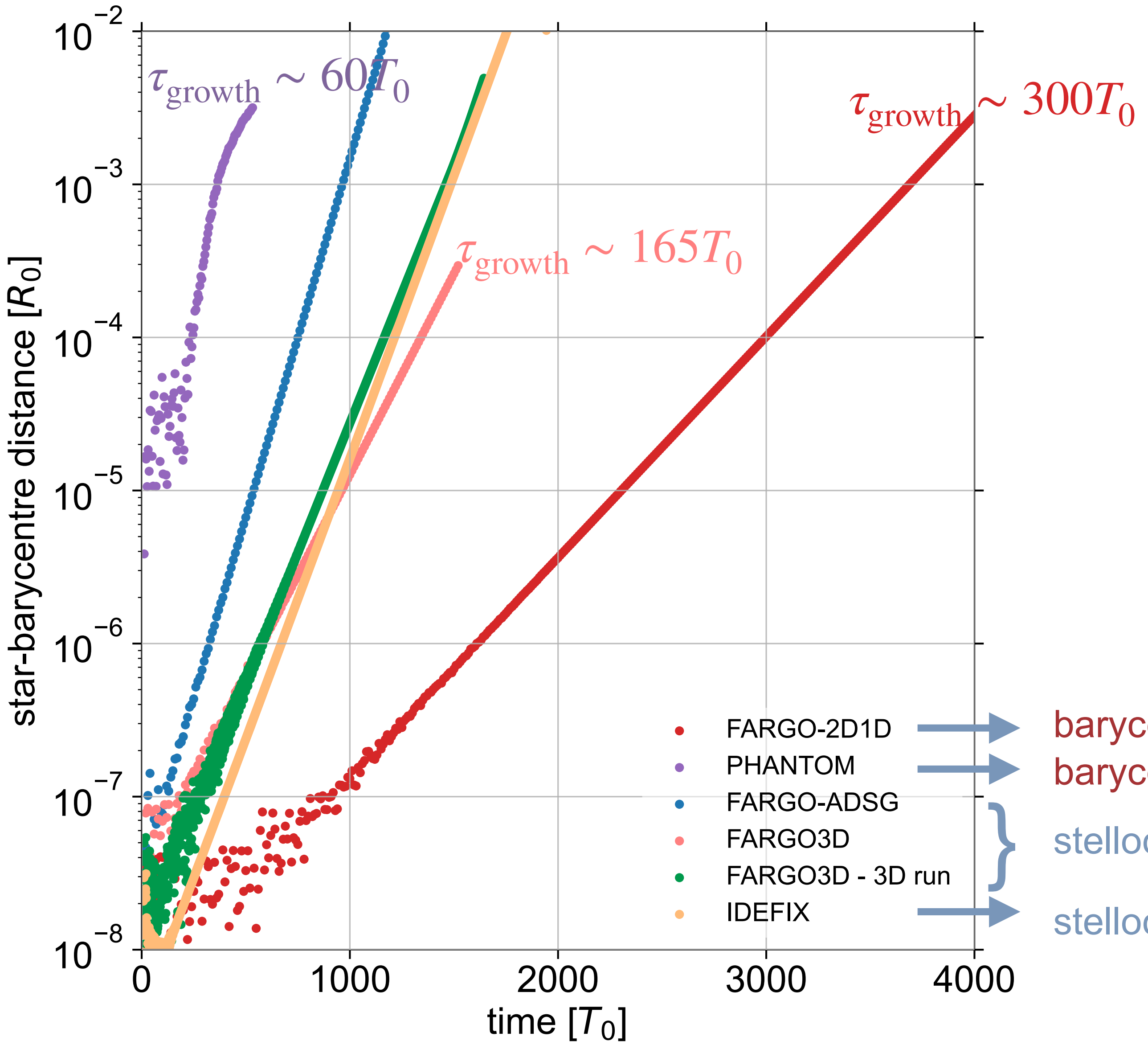
- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a **feedback loop** between an **m=1 mode** in the disc and the **reflex motion** of the **star** around the centre-of-mass → "the reflex instability"
  - instability **disappears** if **reflex** motion is artificially **suppressed**



The reflex instability in protoplanetary discs

Crida, Baruteau, Gonzalez+ 2025b

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a **variety** of **codes**



FARGO-2D1D → barycentric, finite difference grid-based code

PHANTOM → barycentric, Smoothed Particle Hydrodynamics code (0.5M pcs)

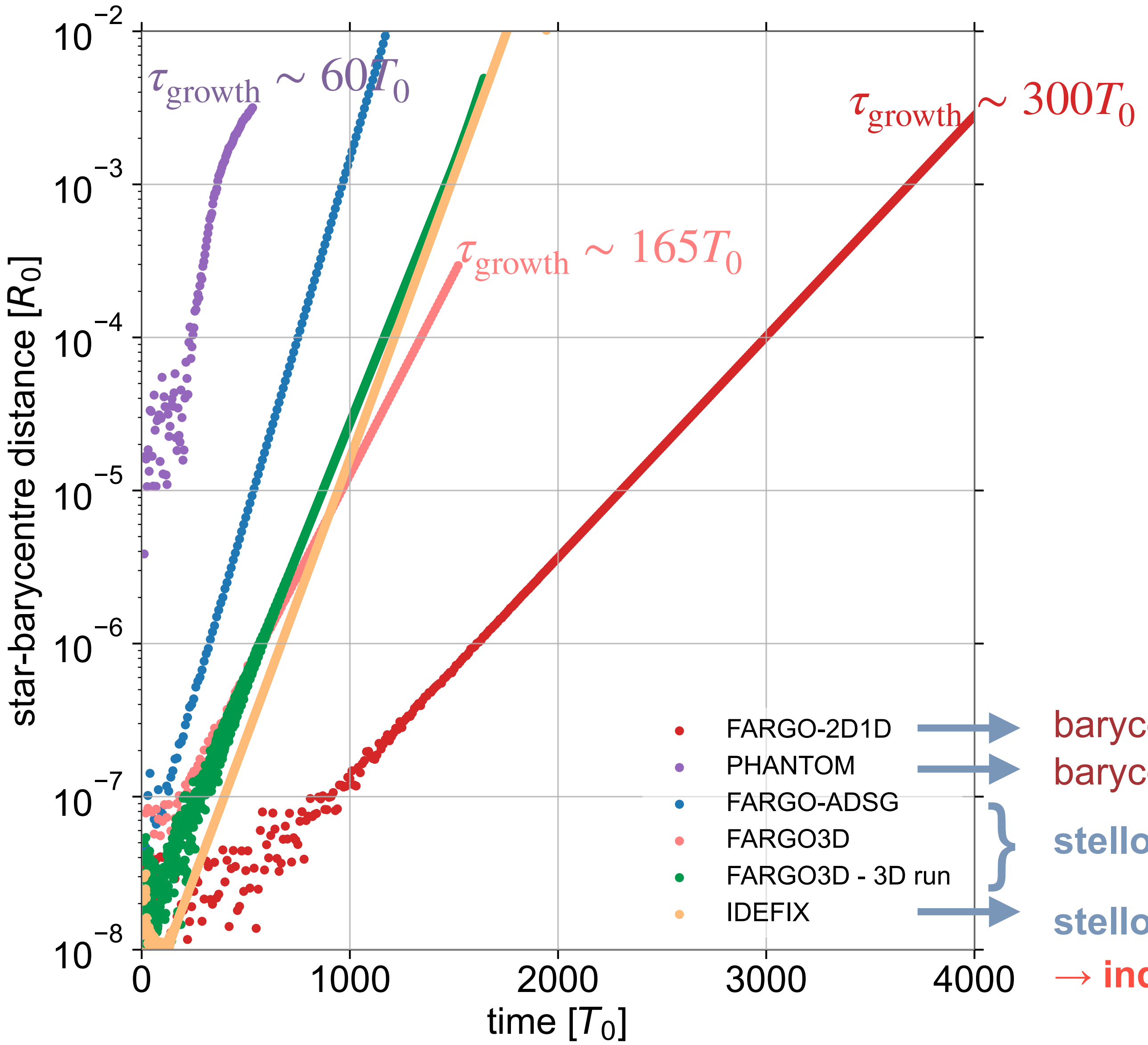
FARGO-ADSG, FARGO3D, FARGO3D - 3D run → stellocentric, finite difference, grid-based code

IDEFIX → stellocentric, finite volume, grid-based code

The reflex instability in protoplanetary discs

Crida, Baruteau, Gonzalez+ 2025b

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a **variety** of **codes**



barycentric, finite difference grid-based code

barycentric, Smoothed Particle Hydrodynamics code (0.5M pcs)

stellocentric, finite difference, grid-based code

stellocentric, finite volume, grid-based code

→ **indirect terms** (**fictitious** forces) used to model star's **reflex** motion

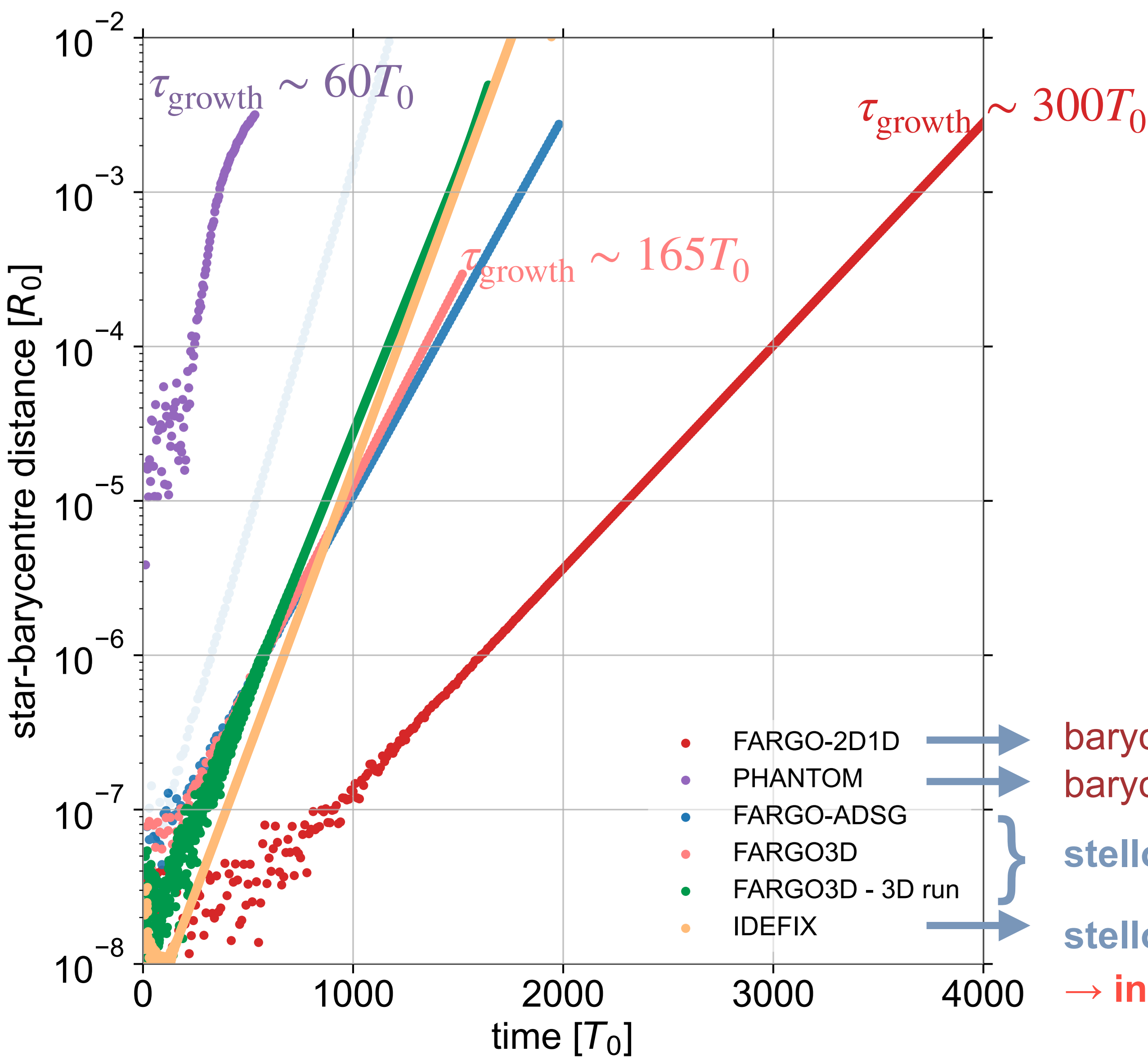
Crida, Baruteau, Griveaud+ 25a

The reflex instability in protoplanetary discs

Crida, Baruteau, Gonzalez+ 2025b

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is (much) **sensitive** to **numerics**

→ **boundary conditions in grid-based codes**



barycentric, finite difference grid-based code

barycentric, Smoothed Particle Hydrodynamics code (0.5M pcs)

stellocentric, finite difference, grid-based code

stellocentric, finite volume, grid-based code

→ **indirect terms** (**fictitious** forces) used to model star's reflex motion

Crida, Baruteau, Griveaud+ 25a

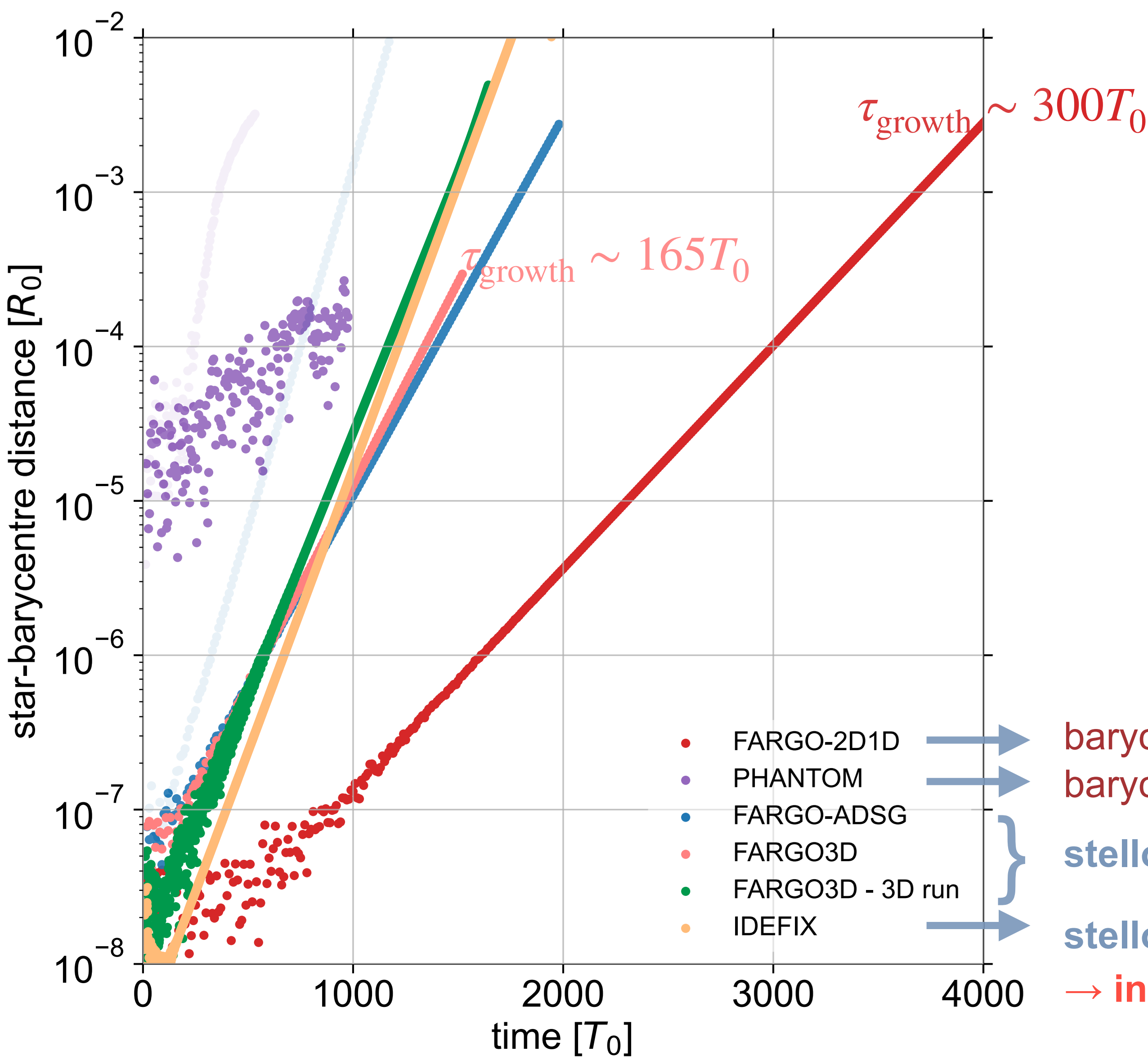
The reflex instability in protoplanetary discs

Crida, Baruteau, Gonzalez+ 2025b

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is (much) **sensitive** to **numerics**

→ **boundary conditions in grid-based codes**

→ **handling of timestep in SPH codes**



barycentric, finite difference grid-based code

barycentric, Smoothed Particle Hydrodynamics code (0.5M pcs)

stellocentric, finite difference, grid-based code

stellocentric, finite volume, grid-based code

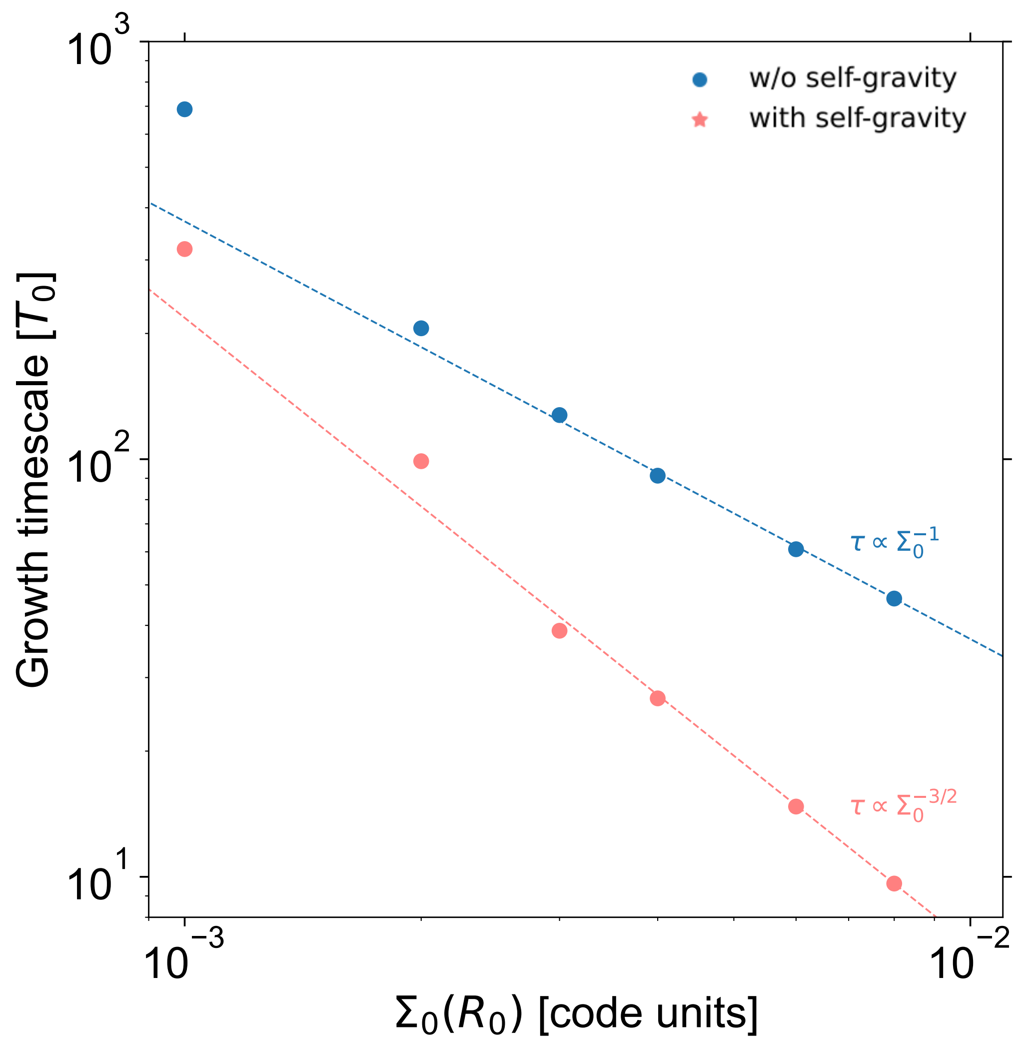
→ **indirect terms** (**fictitious** forces) used to model star's reflex motion

Crida, Baruteau, Griveaud+ 25a

The reflex instability in protoplanetary discs

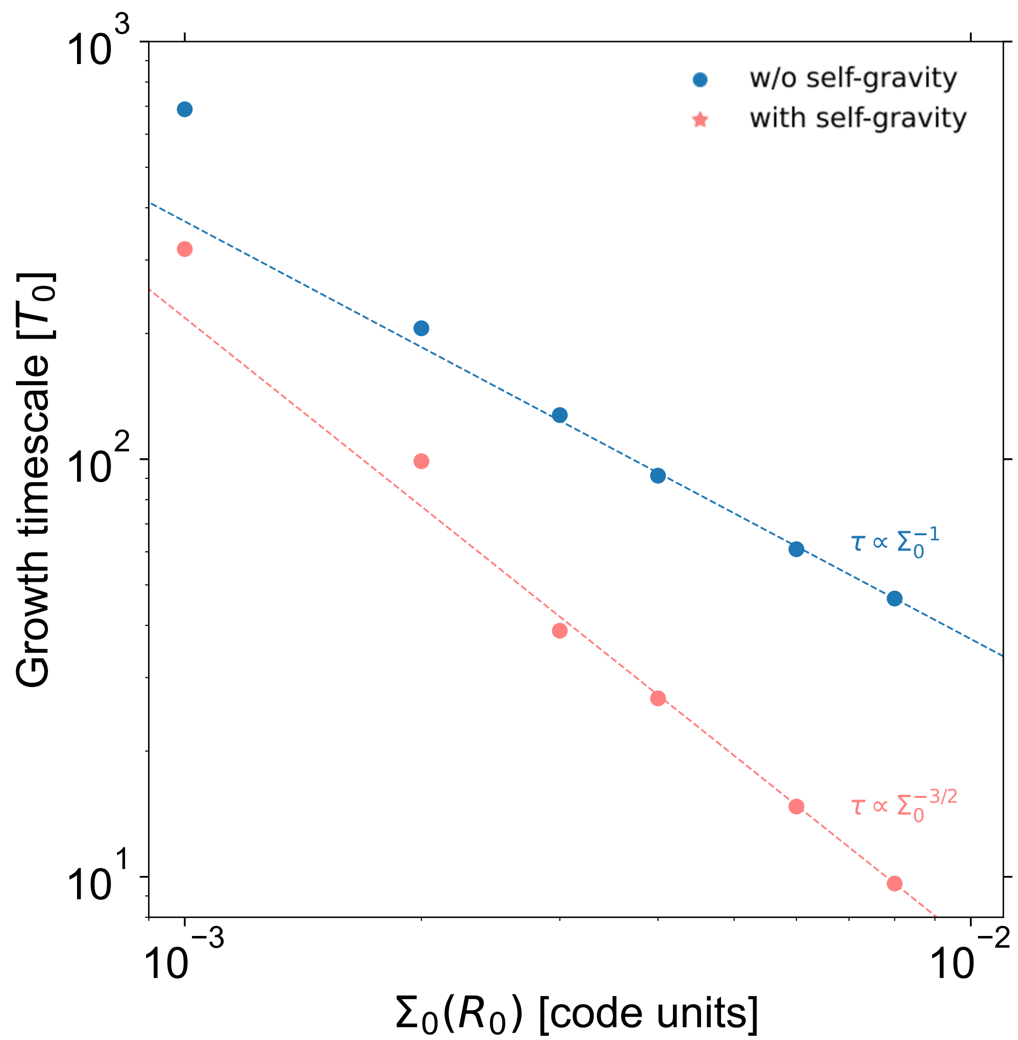
Crida, Baruteau, Gonzalez+ 2025b

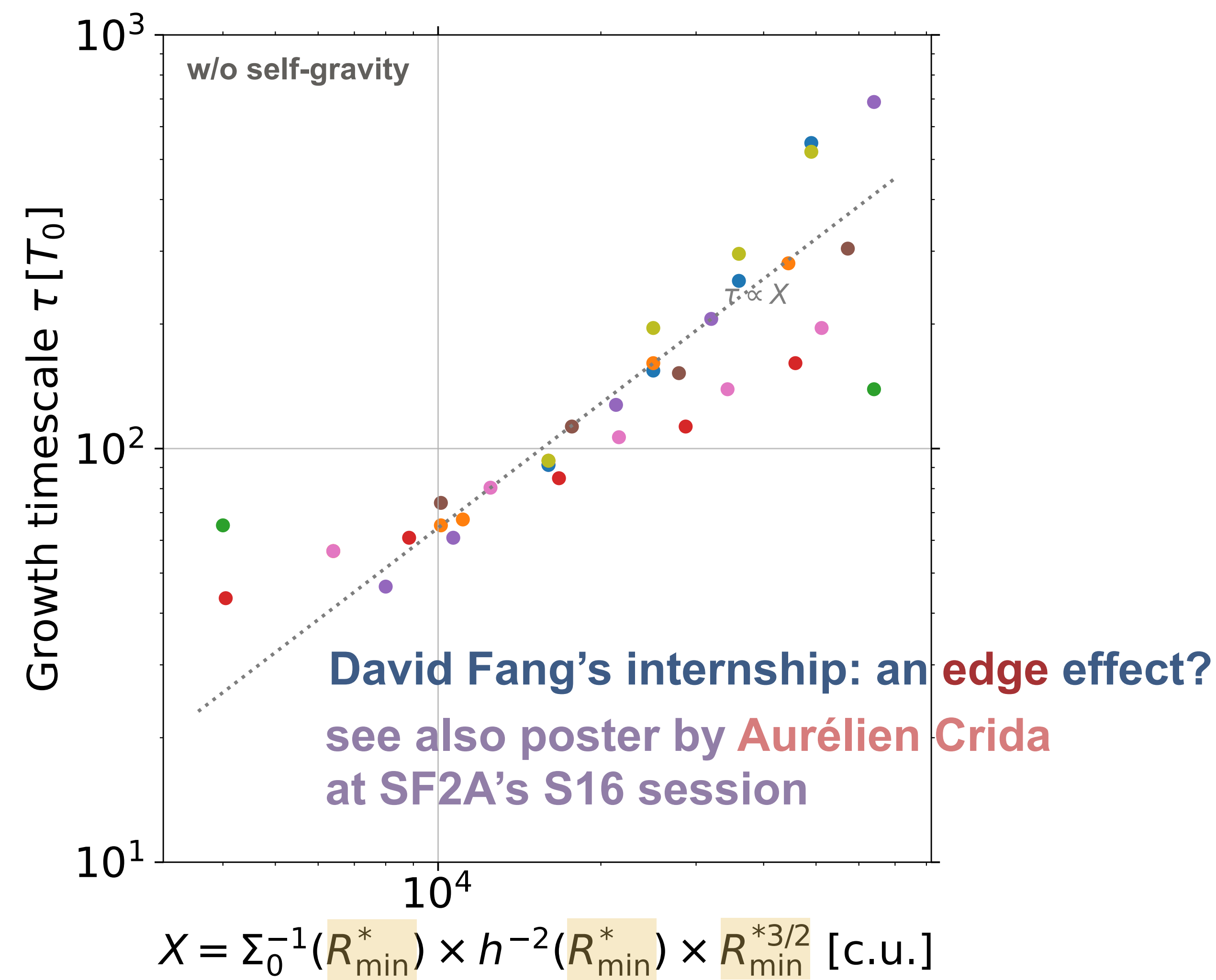
- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary **characterisation** of instability



The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary **characterisation** of instability

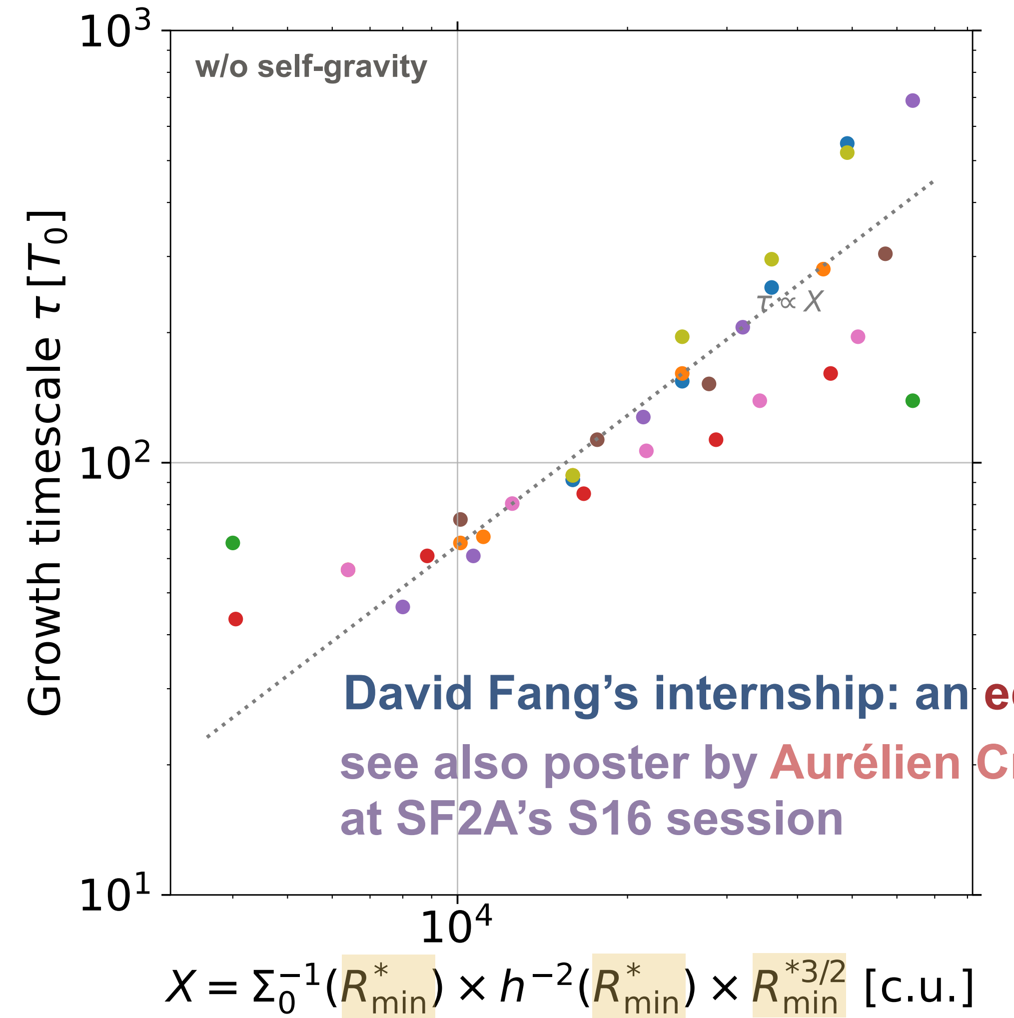




The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary **characterisation** of instability

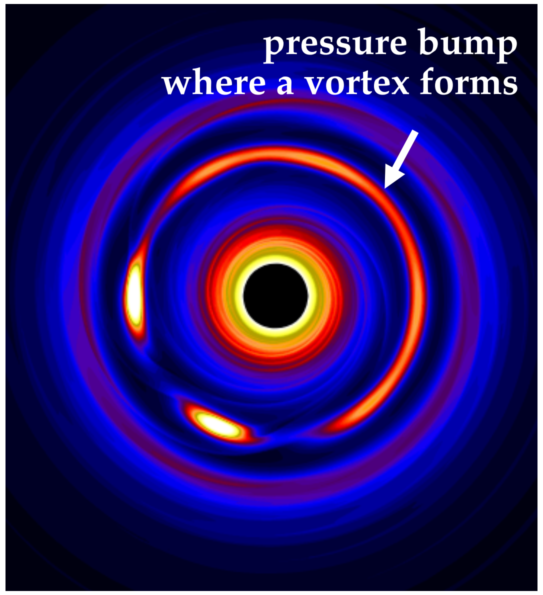
→ instability growth **timescale** ~ a **few thousand years** at the expected inner edge of protoplanetary discs (taken to be the magnetospheric radius), for typical mass accretion rates (~10^{-8} $M_\odot$ yr^{-1})



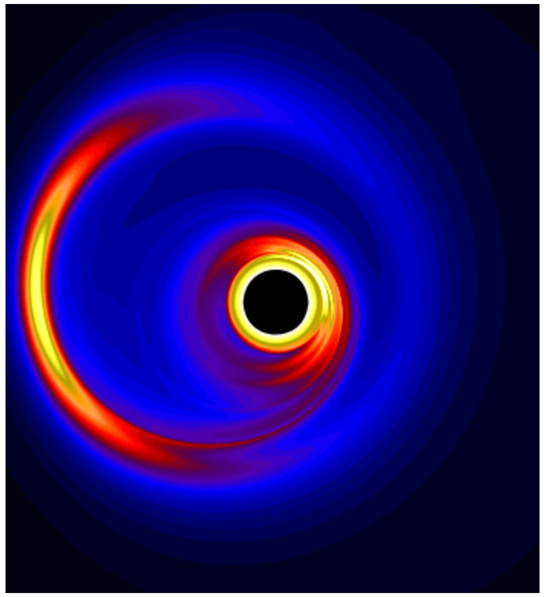
David Fang's internship: an edge effect?
see also poster by Aurélien Crida at SF2A's S16 session

The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary characterisation of instability
- Instability **frequently** seen in other contexts, most often in **massive** discs simulations



WITHOUT DISC INDIRECT TERM

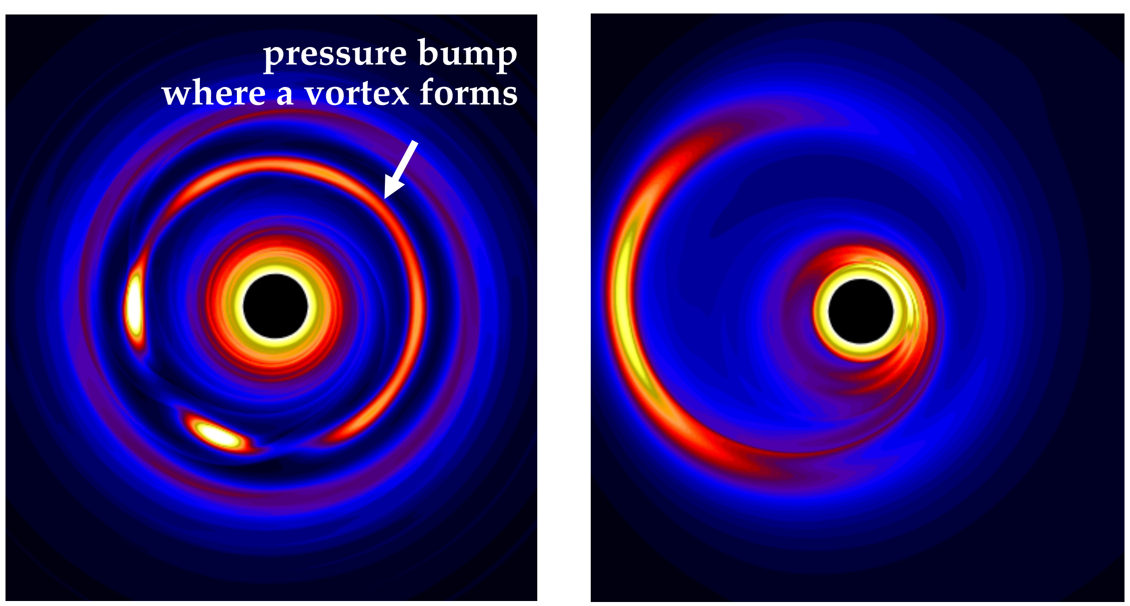


WITH DISC INDIRECT TERM

Pierens & Lin 18

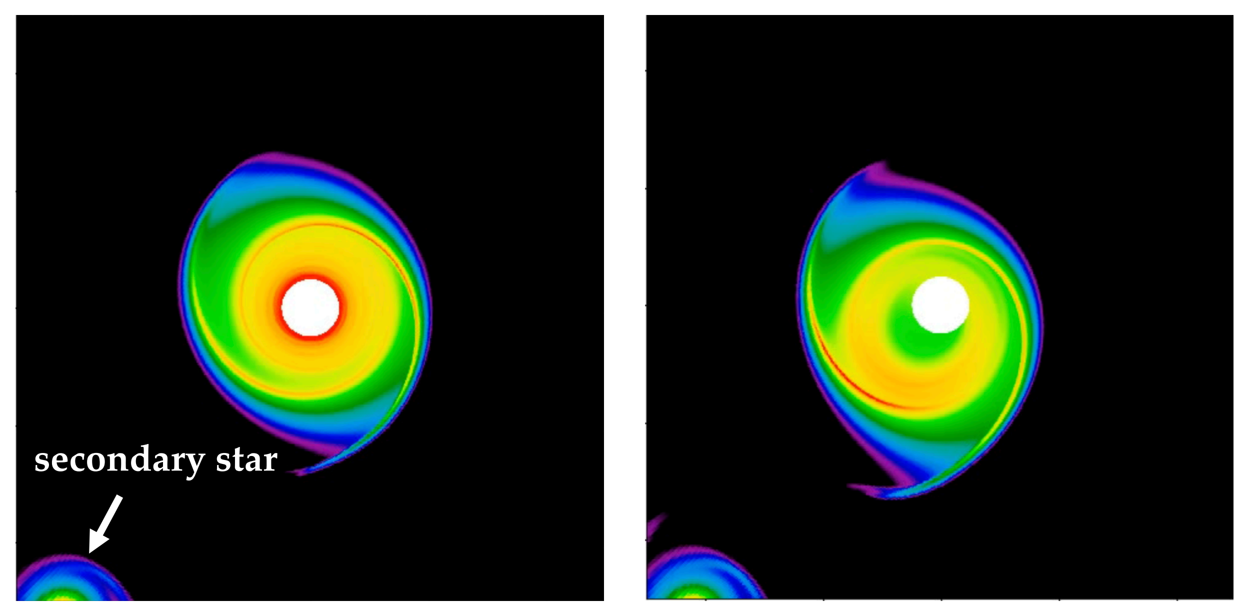
The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary characterisation of instability
- Instability **frequently** seen in other contexts, most often in **massive** discs simulations



WITHOUT DISC INDIRECT TERM | WITH DISC INDIRECT TERM

Pierens & Lin 18

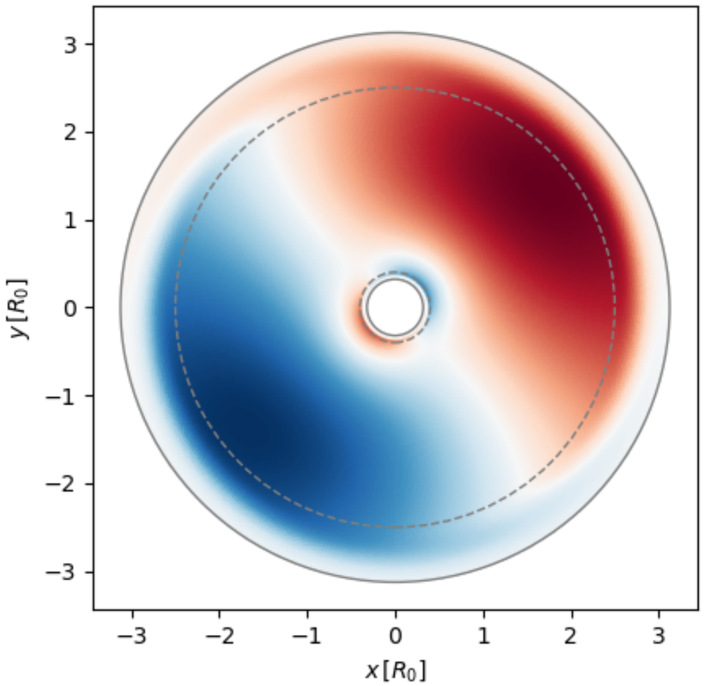


WITHOUT DISC INDIRECT TERM | WITH DISC INDIRECT TERM

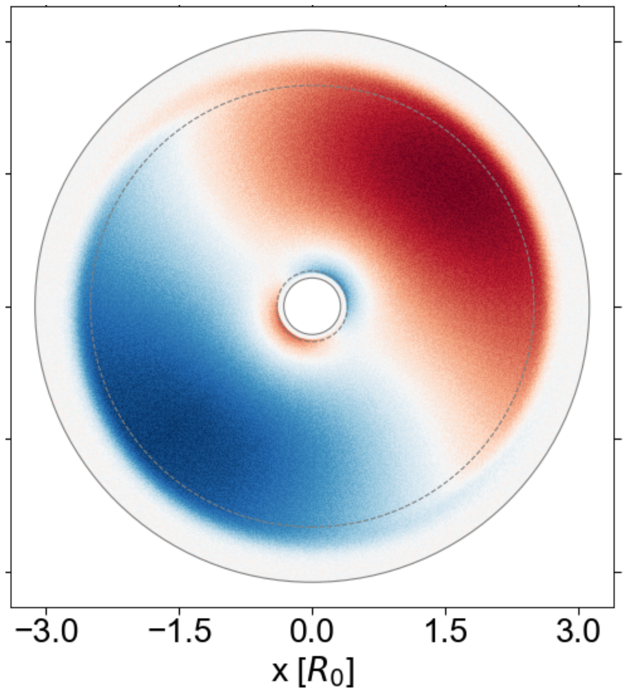
binary disc simulation

The reflex instability in protoplanetary discs

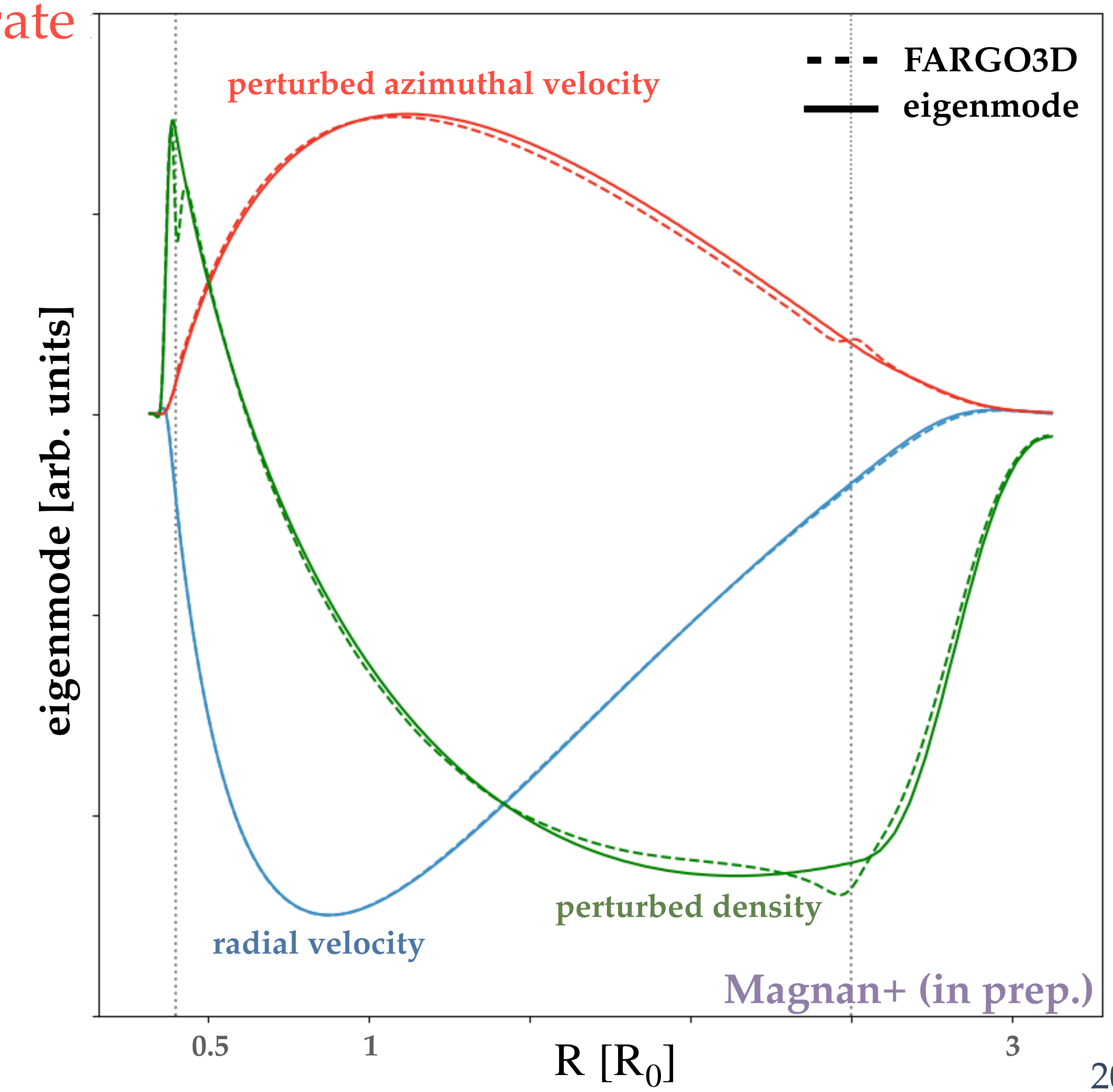
- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate
- Preliminary characterisation of instability
- Instability frequently seen in other contexts
- **Ongoing**: **linear** analysis (Nathan Magnan)



perturbed density in Nathan's code



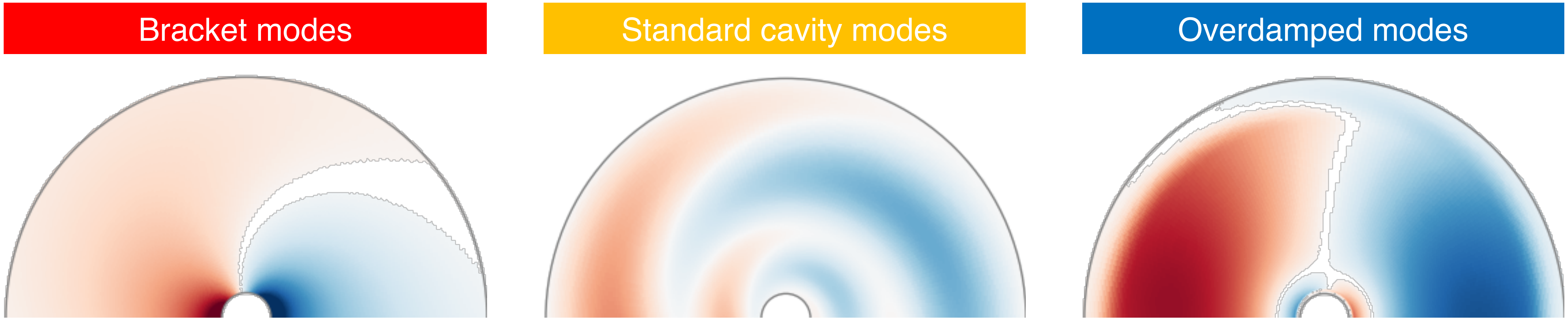
perturbed density in FARGO3D



Magnan+ (in prep.)

The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary characterisation of instability
- Instability frequently seen in other contexts
- **Ongoing: linear** analysis (Nathan Magnan)
  - The reflex motion of the star can induce many **waves** and **instabilities**



Magnan+ (in prep.)
see also talk by Nathan Magnan at SF2A's S09 session

The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary characterisation of instability
- Instability frequently seen in other contexts
- **Ongoing**: **linear** analysis (Nathan Magnan)
  - The reflex motion of the star can induce many **waves** and **instabilities**
  - As far as we can tell, they are all determined by **boundary conditions**

The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary characterisation of instability
- Instability frequently seen in other contexts
- **Ongoing**: **linear** analysis (Nathan Magnan)
  - The reflex motion of the star can induce many **waves** and **instabilities**
  - As far as we can tell, they are all determined by **boundary conditions**
  - There is no obvious way to **predict** them as they are **sensitive** to pretty much everything

The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary characterisation of instability
- Instability frequently seen in other contexts
- **Ongoing**: **linear** analysis (Nathan Magnan)
    - The reflex motion of the star can induce many **waves** and **instabilities**
    - As far as we can tell, they are all determined by **boundary conditions**
    - There is no obvious way to **predict** them as they are **sensitive** to pretty much everything
    - There is no obvious way to **avoid** them

The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary characterisation of instability
- Instability frequently seen in other contexts
- **Ongoing**: **linear** analysis (Nathan Magnan)
    - The reflex motion of the star can induce many **waves** and **instabilities**
    - As far as we can tell, they are all determined by **boundary conditions**
    - There is no obvious way to **predict** them as they are **sensitive** to pretty much everything
    - There is no obvious way to **avoid** them
    - The only **safe** option would be to model **the entire disc** from its **inner cavity** (if there) to its **outer edge**

The reflex instability in protoplanetary discs

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary characterisation of instability
- Instability frequently seen in other contexts
- **Ongoing**: linear analysis (Nathan Magnan), simulations to examine non-linear **saturation** of instability, its **implications** on disc evolution, planet formation & evolution

The reflex instability in protoplanetary discs

Crida, Baruteau, Gonzalez+ 2025b

- It all started with long-term 2D hydrodynamical simulations of disc-planet interactions
- We then adopted a planet-free, but still deliberately simple disc model
- Instability is linear, non-axisymmetric, global
- Arises from a feedback loop between an m=1 mode in the disc and the reflex motion of the star around the centre-of-mass
- It is found in a variety of codes, its growth rate is sensitive to numerics
- Preliminary characterisation of instability
- Instability frequently seen in other contexts
- Ongoing: linear analysis (Nathan Magnan), simulations to examine non-linear saturation of instability, its implications on disc evolution, planet formation & evolution

... thanks!